

NASA/TM—2000–209891, Vol. 150



**Technical Report Series on the  
Boreal Ecosystem-Atmosphere Study (BOREAS)**

*Forrest G. Hall and Andrea Papagno, Editors*

**Volume 150**

**BOREAS TE-7 Sap Flow Data**

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October 2000

Available from:

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# BOREAS TE-7 Sap Flow Data

E.H. Hogg, P.A. Hurdle

## Summary

The BOREAS TE-7 team collected data sets in support of its efforts to characterize and interpret information on the sap flow of boreal vegetation. The heat pulse method was used to monitor sap flow and to estimate rates of transpiration from aspen, black spruce, and mixed wood forests at the SSA-OA, MIX, SSA-OBS, and Batoche sites in Saskatchewan, Canada. Measurements were made at the various sites from May to October 1994, May to October 1995, and April to October 1996. A scaling procedure was used to estimate canopy transpiration rates from the sap flow measurements. The data were stored in tabular ASCII files.

Analyses to date show a tendency for sap flow in aspen to remain remarkably constant over a wide range of environmental conditions VPD from 1.0 to 4.8 kPa and solar radiation  $>400 \text{ W/m}^2$ ). For forests with high aerodynamic conductance, the results would indicate an inverse relationship between stomatal conductance and VPD, for VPD  $>1 \text{ kPa}$ . A possible interpretation is that stomata are operating to maintain leaf water potentials above a critical minimum value, which in turn places a maximum value on the rate of sap flow that can be sustained by the tree.

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## 1. Data Set Overview

### 1.1 Data Set Identification

BOREAS TE-07 Sap Flow Data

### 1.2 Data Set Introduction

Sap flow and transpiration of trees were measured in the southern boreal forest and aspen parkland of western Canada as part of the BOREal Ecosystem-Atmosphere Study (BOREAS) during the years of 1994, 1995, and 1996. These data sets contain data on the rate of flow of sap (water) in tree stems during the growing season (beginning April to June and ending in October). Also included are a

limited number of environmental measurements (air temperature and relative humidity, and in some instances, solar radiation and wind speed). Measurements were made every 3 hours in 1994 and hourly in 1995-96.

### 1.3 Objective/Purpose

The objectives of this research were to:

- Examine how forest transpiration at different time scales (diurnal and seasonal) is affected by environmental conditions, including vapor pressure deficit (VPD), solar radiation, temperature, wind, and soil moisture.
- Use sap flow measurements, coupled with environmental measurements, as a means of examining changes in canopy (stomatal) conductance in aspen and spruce.
- Compare transpiration responses of aspen under two contrasting climates (boreal site at Southern Study Area (SSA) Old Aspen (SSA-OA), and drought-prone aspen parkland site at Batoche, located 100 km south of SSA-OA).
- Ultimately, through collaboration with other BOREAS investigators, determine what is controlling rates of forest transpiration at different time scales.
- On a long-term scale, use this information as part of the foundation for the development of carbon-based, daily time-step models of forest growth responses to changes in climate.

### 1.4 Summary of Parameters

Air temperature

Relative humidity

Sap flux density (cm<sup>3</sup> per cm<sup>2</sup> of sapwood area per hour)

Soil moisture (10 and 30 cm depths, Batoche site only)

Vapor pressure

### 1.5 Discussion

In the western Canadian interior, regional climatic moisture gradients appear to be closely linked to forest distribution and to hydrological differences in ecosystem functioning (Hogg, 1994, 1997). Thus, an understanding of the factors controlling forest transpiration is especially important in this region, and is critical to predicting how the productivity and hydrology of the boreal forest would respond to a warmer and drier future climate.

One of the major processes being studied in the BOREAS project is water vapor flux from different vegetation types and its control by environmental and ecophysiological factors (Sellers et al., 1995). A major component of the research within BOREAS has been to monitor xylem sap flux (upward flow of water) within individual trees during the growing season. The attempt is then made to "scale up" these results to give transpiration estimates at the stand level, using measurements and estimates of stand and sapwood characteristics. The accuracy of the scaling procedure can then be assessed through comparisons with eddy correlation measurements made above and below the tree canopy.

The research described here was conducted by two members of the Canadian Forest Service (CFS), Edmonton, who are members of the Terrestrial Ecology (TE) group, team TE-07, within BOREAS. This work was conducted as part of the CFS Climate Change program, and is also a contribution to the CFS Boreal Forest Transect Case Study (BFTCS; see Price and Apps, 1995).

The heat pulse method was used to monitor sap flow continuously during the growing season from May to October (for details, see Section 3, Theory of Measurements). All measurements were made in the SSA. At the OA site, sap flow was measured on six aspen (*Populus tremuloides*) trees near the flux tower in 1996 and near the TE tower in 1994. At the Batoche site, 9 to 12 aspen trees were measured during 1994-96. At the Mixed wood site (MIX), four aspen, two white spruce (*Picea glauca*), and two black spruce (*Picea mariana*) were measured in 1994. At the Old Black Spruce (OBS) site, six black spruce were measured in 1996. Sap flow was measured every 3 hours at all sites in 1994, and hourly in 1995 and 1996.

Hourly meteorological data were obtained from the 18-m tower and at each of four sap flow stations at Batoche. Limited environmental measurements were made from sap flow stations at BOREAS sites.

In the data files, the column called MEASUREMENT\_DESCR gives a coded description of the measurements taken. Each measurement taken is denoted by a single letter of code. The description code is:

- "a" to "h" means that trees called "a" to "h" gave good data.
- "N" denotes trees receiving new probes.
- "x" denotes missing or bad data taken from that tree.

### **1.6 Related Data Sets**

BOREAS TE-11 Sap Flow Data

BOREAS TE-11 Leaf Gas Exchange Measurements

BOREAS RSS-17 Xylem Flux Density Measurements at the SSA-OBS Site

## **2. Investigator(s)**

### **2.1 Investigator(s) Name and Title**

E.H. (Ted) Hogg

Research Scientist

Climate Change Network

Canadian Forest Service

### **2.2 Title of Investigation**

Climate Change Effects on Net Primary Productivity of Productivity of Aspen and Jack Pine at the Southern Limit of the Boreal Forest

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### 3. Theory of Measurements

Sap (water) flow was measured by the heat pulse method (Marshall, 1958; Swanson, 1983, 1994; Hogg et al., 1997), using two thermocouples spaced symmetrically 0.75 cm above and below a heater 5-cm long with a power output of 2 W/cm. All probe elements had a diameter of 1.6 mm, and holes of the same diameter were drilled using a steel template. Thermocouple depth in the sapwood was 1.5 cm for large (>15 cm diameter) trees and 1.0 cm for smaller trees. At the SSA-OBS site, a depth of 7.5 mm was used because of narrow (4 to 12 mm) sapwood under a bark width of about 3-4 mm.

Probes were located at a height of approximately 1.3 m on the north side of the tree and were thermally insulated by wrapping with them white polyethylene packing material. At each station, a datalogger (Campbell Scientific, Model 21X, powered by batteries and a solar panel) was used to record the temperature increase at the upper ( $T_u$ ) and lower ( $T_l$ ) thermocouples, 60 s following a 4-s heat pulse. On two dates in 1994 (boreal site, Julian Day of Year (DOY) 192 and 209; parkland site, DOY 190 and 205), one or two probes per station were removed and replaced with new probes at another location on the same tree (all probes were replaced once). In 1995 and 1996, probes were replaced only as needed, i.e., following heater failure or abnormal wounding.

### 4. Equipment

#### 4.1 Sensor/Instrument Description

The sap flow instrumentation was designed and constructed by P.A. Hurdle at the CFS. The instrumentation has evolved from earlier implementations used by P.A. Hurdle and R.H. Swanson, former research scientist at CFS (retired 1992).

The system operates using Campbell Scientific dataloggers (Model 21x). Measurements of temperature and relative humidity were made using shielded Model HMP35C Vaisala probes. Volumetric water content of the soil was measured using Barber-Colman fiberglass sensors that had been precalibrated in the laboratory using soil samples collected from the site (Batoche only).

#### 4.1.1 Collection Environment

Measurements were made with ambient environmental conditions of forest understories, from April or May to October. Temperatures ranged from -10 to 35 (C). Occasional damage to sap flow probes was caused by bears, deer, and other wildlife, which usually resulted in complete malfunction of probes in affected trees. Lightning and rain events did not adversely affect the operation of the instruments.

#### 4.1.2 Source/Platform

Probes were mounted at a height of 1 to 1.5 m on the north side of trees. The datalogger was in a weatherproof box, anchored either to a wooden fence or to an adjacent tree. Environmental measurements were made either from a tripod or from a horizontally mounted aluminum boom extending from a fencepost or pole.

#### **4.1.3 Source/Platform Mission Objectives**

The platform objective was to provide a place from which accurate and consistent measurements could be made.

#### **4.1.4 Key Variables**

- sap flux density (cm<sup>3</sup> per cm<sup>2</sup> of sapwood area per hour)
- sapwood area to ground area ratio

For analysis (including collaborations with other investigators):

- hourly in-canopy (derived from air temperature and relative humidity)
- hourly solar radiation
- daily precipitation and soil moisture
- leaf area index
- aerodynamic conductance (to assess degree to which VPD versus net radiation is controlling transpiration using the Penman-Monteith approach)

#### **4.1.5 Principles of Operation**

A probe placed in the sapwood released a pulse of heat. One minute later, the increase in sapwood temperature 7.5 mm above and below the heater was measured using thermocouples. If no sap (water) is flowing, the temperature increase is symmetrical; as sap flow increases, more heat is transported to the upper heater and less heat reaches the lower heater. Sap flow is proportional to the natural logarithm of the ratio between the temperature increase of the upper thermocouple and that of the lower thermocouple. The calculation also required estimates of sapwood bulk density and moisture content, and a correction factor needed to be applied to account for interruption of the sap stream by probes.

#### **4.1.6 Sensor/Instrument Measurement Geometry**

The heater provided a linear heat source across the full sapwood depth. The thermocouples were located at an appropriate sapwood depth (0.75 to 1.5 cm, depending on sapwood thickness).

#### **4.1.7 Manufacturer of Sensor/Instrument**

Barber-Colman Fiberglass Sensors  
Barber-Colman Company  
103 High St.  
P.O. Box 1067  
Sutton West ON L0E 1R0  
Canada  
(905) 722-9881  
(905) 722-4260 (fax)  
bc@ils.com

Campbell Scientific Dataloggers  
Model CR21x  
Campbell Scientific, Inc.  
815 West 1800 North  
Logan, UT 84321-1784  
(435) 753-2342  
(435) 750-9540 (fax)  
support@campbellsci.com

Sap flow Instrumentation  
Custom-designed by P.A. Hurdle (address given in Section 2.3)

VAISALA Oyj Probe  
Model HMP35C  
P.O. Box 26 FIN-00421 Helsinki  
FINLAND  
(+358 9) 894 91  
(+358 9) 894 9227 (fax)  
122832 vsala fi (telex)

## **4.2 Calibration**

Calibrations of earlier designs have been conducted on small trees in the laboratory by Cohen et al. (1981) and Swanson (1983), but field calibration was difficult (e.g., on 20-m-tall aspen trees). A heat transfer model, similar to that used by Swanson and Whitfield (1981), was used to determine the degree to which sap flux densities were underestimated through local interruption of sap flow by probes. The primary means of calibration at the stand level was to compare results against other sap flow methods and against eddy correlation measurements of latent heat flux (Hogg et al., 1997; see also Black et al., 1996).

### **4.2.1 Specifications**

Freezing and thawing of xylem during early spring and late fall result in "spiking" of sap flow outputs. The sap flow calculation was insensitive to the quantity of heat released by the probe (although signal-to-noise ratio can be affected if power output of heater decreases, e.g., by weak solar panels and batteries).

#### **4.2.1.1 Tolerance**

As shown by Hogg and Hurdle (1997), TE-07's implementation was highly sensitive to slow rates of sap flow (as would be recorded at night); sap flow rates corresponding to 5 to 10% of the typical midday maximum can be easily resolved.

The spacing of thermocouples relative to the heater (0.75 cm) allowed measurements of sap flow rates (S) of up to about 12 cm/h. If sap flow was greater than this, there would be no detectable temperature increase at the lower thermocouple. Such over-ranging was never observed in aspen or spruce using the 0.75 cm spacing, but over-ranging was observed in early trials using a spacing of 1.0 cm.

A slight nonlinearity of sensitivity may have occurred as a result of sap flow. This was largely covered by the inflow interruption by the probes; based on the heat transfer modeling, sap flow may be underestimated by up to 10% at the maximum measurable rate. Laboratory comparisons by Swanson (1983, p. 177) using lysimetry with small aspen showed little evidence of nonlinearity, even though heat transfer simulations by Swanson and Whitfield (1981) predicted a significant nonlinear response for some implementations of the heat pulse method.

### **4.2.2 Frequency of Calibration**

Inspections and maintenance of instrumentation were conducted every 2 to 4 weeks (more frequently during Intensive Field Campaigns (IFCs)). There were no means by which to calibrate sap flow estimates or transpiration estimates, except by comparisons against other methods.

### **4.2.3 Other Calibration Information**

Not applicable.

## 5. Data Acquisition Methods

At each station, data from three or four trees were stored every 3 hours (1994) or every hour (1995 and 1996) by a Campbell Scientific datalogger (Model 21X). For sap flow, the temperature increase above and below the heater was reported 1, 2, and 3 minutes following the heat pulse, for each tree being measured. With the amount of data reported and the datalogger used, up to 27 days of hourly time-step sap flow results for three trees could be stored. A cassette tape was also used as backup data storage, in the event of a power loss to the datalogger or in case the period between field visits extended beyond this amount of time. Data were downloaded from the datalogger onto a laptop computer.

## 6. Observations

### 6.1 Data Notes

In the data files, the column called MEASUREMENT\_DESCR gives a coded description of the measurements taken. Each measurement taken is denoted by a single letter of code. The description code is:

- "a" to "h" means that trees called "a" to "h" gave good data.
- "N" denotes trees receiving new probes.
- "x" denotes missing or bad data taken from that tree.

See Section 11.4.

### 6.2 Field Notes

See Section 11.4.

## 7. Data Description

### 7.1 Spatial Characteristics

#### 7.1.1 Spatial Coverage

All sap flow measurements were made on individual trees. Three or four trees, all located within a 10-m x 10-m plot, were measured at each sap flow monitoring station. As part of the scaling procedure used to estimate stand transpiration rates from sap flow results, tallies of the diameters of each tree within the 10-m x 10-m plot were made to estimate the local ratio between stand basal area and ground area (i.e., 100 m<sup>2</sup> area). The number of sap flow monitoring stations at each SSA site (Ns), number of trees (Nt) per station, and maximum distance separating stations are given below:

Site	Year	Ns	Nt	Distance
SSA-OA	1994	2	3	ca. 20 m
MIX	1994	2	4	ca. 30 m
Batoche	1994	3	3	ca. 300 m
Batoche	1995	3	3	ca. 300 m
SSA-OA	1996	2	3	ca. 100 m
SSA-OBS	1996	2	3	ca. 100 m

The SSA measurement sites and associated North American Datum of 1983 (NAD83) coordinates are:

- SSA-OA flux tower, site id C3B7T, Lat/Long: 53.62889° N, 106.19779° W, Universal Transverse Mercator (UTM) Zone 13, N: 5,942,899.9, E: 420,790.5.
- SSA-OA TE tower, located 100 m from the dirt road, site id C3B7T, Lat/Long: 53.62889° N, 106.19779° W, UTM Zone 13, N: 5,942,899.9, E: 420,790.5.
- ASP-AUX01 Batoche, site id A1A, Lat/Long: 52.74244° N, 106.13372° W, UTM Zone 13, N: 5,844,222, E: 423,465.
- MIX TE tower, site id D9I1M, Lat/Long: 53.7254° N, 105.20643° W, UTM Zone 13, N: 5,952,989.7, E: 486,379.7.
- SSA-OBS flux tower, site id G8I4T, Lat/Long: 53.98717° N, 105.11779° W, UTM Zone 13, N: 5,982,100.5, E: 492,276.5.

### 7.1.2 Spatial Coverage Map

Not applicable.

### 7.1.3 Spatial Resolution

These are point measurements made at the given locations.

### 7.1.4 Projection

Not applicable.

### 7.1.5 Grid Description

Not applicable.

## 7.2 Temporal Characteristics

### 7.2.1 Temporal Coverage

The data were collected from 23-May-1994 to 23-Oct-1996.

### 7.2.2 Temporal Coverage Map

Site	Measurement Dates
SSA-OA	26-May-1994 to 20-Oct-1994 (DOY 146-293)
SSA MIX	13-Jun-1994 to 20-Oct-1994 (DOY 164-293)
Batoche	23-May-1994 to 19-Oct-1994 (DOY 143-292)
Batoche	21-May-1995 to 25-Oct-1995 (DOY 141-298)
SSA-OA	19-Apr-1996 to 23-Oct-1996 (DOY 110-297)
SSA-OBS	13-Apr-1996 to 22-Oct-1996 (DOY 104-296)

The sampling interval was always the same, regardless of IFC.

### 7.2.3 Temporal Resolution

Measurement occurred between 00 and 01 minutes after each hour; 1994 measurements began at 00, 03, 06, 09, 12, 15, 18, 21 hour Greenwich Mean Time (GMT), and 1995 and 1996 measurements began on the hour, every hour.

## 7.3 Data Characteristics

### 7.3.1 Parameter/Variable

The parameters contained in the data files on the CD-ROM are:

Column Name
SITE_NAME
SUB_SITE
DATE_OBS
TIME_OBS
SPECIES
TREE_DESCR
MEASUREMENT_DESCR
NUM_TREES
SAPFLOW_RATE
MEAN_SAPFLOW_RATE
MEAN_TRANS_RATE
MEAN_AIR_TEMP_1HR_150CM
MEAN_REL_HUM_1HR_150CM
MEAN_AIR_TEMP_3HR_240CM
MEAN_REL_HUM_3HR_240CM
MEAN_AIR_TEMP_1HR_25M
MEAN_VAPOR_PRESS_1HR_25M
MEAN_DOWN_SHRTWAVE_RAD_3HR_4M
MEAN_DOWN_SHRTWAVE_RAD_1HR_18M
MEAN_WIND_VELOCITY_1HR_18M
CRTFCN_CODE
REVISION_DATE

### 7.3.2 Variable Description/Definition

The descriptions of the parameters contained in the data files on the CD-ROM are:

Column Name	Description
SITE_NAME	The identifier assigned to the site by BOREAS, in the format SSS-TTT-CCCC, where SSS identifies the portion of the study area: NSA, SSA, REG, TRN, and TTT identifies the cover type for the site, 999 if unknown, and CCCC is the identifier for site, exactly what it means will vary with site type.
SUB_SITE	The identifier assigned to the sub-site by BOREAS, in the format GGGGG-IIIII, where GGGGG is the group associated with the sub-site instrument, e.g. HYD06 or STAFF, and IIIII is the identifier for sub-site, often this will refer to an instrument.
DATE_OBS	The date on which the data were collected.
TIME_OBS	The Greenwich Mean Time (GMT) when the data were collected.
SPECIES	Botanical (Latin) name of the species (Genus species).
TREE_DESCR	Description of the tree sampled.
MEASUREMENT_DESCR	Description of the measurement taken.
NUM_TREES	The number of trees that exist in a particular

SAPFLOW_RATE	plot. The sap flow rate of the sample tree.
MEAN_SAPFLOW_RATE	The mean sap flow rate from the sampled trees.
MEAN_TRANS_RATE	Mean stand transpiration rate estimated from sap flux density.
MEAN_AIR_TEMP_1HR_150CM	The mean hourly air temperature measured at a height of 150 centimeters above the ground.
MEAN_REL_HUM_1HR_150CM	The mean hourly relative humidity measured at a height of 150 centimeters above the ground.
MEAN_AIR_TEMP_3HR_240CM	The air temperature averaged over three hours and taken at a height of 240 centimeters above the ground.
MEAN_REL_HUM_3HR_240CM	The relative humidity averaged over three hours and taken 240 centimeters above the ground.
MEAN_AIR_TEMP_1HR_25M	The hourly mean air temperature measured at a height of 25 meters above the ground.
MEAN_VAPOR_PRESS_1HR_25M	The mean hourly vapor pressure measured at a height of 25 meters above the ground.
MEAN_DOWN_SHRTWAVE_RAD_3HR_4M	The three hour below canopy mean downwelling shortwave radiation measured at a height of 400 centimeters above the ground.
MEAN_DOWN_SHRTWAVE_RAD_1HR_18M	The mean hourly downwelling shortwave radiation measured above the canopy and 18 meters above the ground.
MEAN_WIND_VELOCITY_1HR_18M	The mean hourly wind velocity measured at a height of 18 meters above the ground.
CRTFCN_CODE	The BOREAS certification level of the data. Examples are CPI (Checked by PI), CGR (Certified by Group), PRE (Preliminary), and CPI-??? (CPI but questionable).
REVISION_DATE	The most recent date when the information in the referenced data base table record was revised.

### 7.3.3 Unit of Measurement

The measurement units for the parameters contained in the data files on the CD-ROM are:

Column Name	Units
SITE_NAME	[none]
SUB_SITE	[none]
DATE_OBS	[DD-MON-YY]
TIME_OBS	[HHMM GMT]
SPECIES	[none]
TREE_DESCR	[unitless]
MEASUREMENT_DESCR	[unitless]
NUM_TREES	[counts]
SAPFLOW_RATE	[millimeters][hour <sup>-1</sup> ]
MEAN_SAPFLOW_RATE	[millimeters][hour <sup>-1</sup> ]
MEAN_TRANS_RATE	[millimeters][hour <sup>-1</sup> ]
MEAN_AIR_TEMP_1HR_150CM	[degrees Celsius]
MEAN_REL_HUM_1HR_150CM	[percent]
MEAN_AIR_TEMP_3HR_240CM	[degrees Celsius]
MEAN_REL_HUM_3HR_240CM	[percent]
MEAN_AIR_TEMP_1HR_25M	[degrees Celsius]

MEAN_VAPOR_PRESS_1HR_25M	[pascals]
MEAN_DOWN_SHRTWAVE_RAD_3HR_4M	[watts][meter^-2]
MEAN_DOWN_SHRTWAVE_RAD_1HR_18M	[watts][meter^-2]
MEAN_WIND_VELOCITY_1HR_18M	[meters][second^-1]
CRTFCN_CODE	[none]
REVISION_DATE	[DD-MON-YY]

### 7.3.4 Data Source

The sources of the parameter values contained in the data files on the CD-ROM are:

Column Name	Data Source
SITE_NAME	[BORIS Designation]
SUB_SITE	[BORIS Designation]
DATE_OBS	[Human Observer]
TIME_OBS	[Human Observer]
SPECIES	[Human Observer]
TREE_DESCR	[Human Observer]
MEASUREMENT_DESCR	[Human Observer]
NUM_TREES	[Human Observer]
SAPFLOW_RATE	[Laboratory Equipment]
MEAN_SAPFLOW_RATE	[Laboratory Equipment]
MEAN_TRANS_RATE	[Laboratory Equipment]
MEAN_AIR_TEMP_1HR_150CM	[Thermometer]
MEAN_REL_HUM_1HR_150CM	[Laboratory Equipment]
MEAN_AIR_TEMP_3HR_240CM	[Thermometer]
MEAN_REL_HUM_3HR_240CM	[Laboratory Equipment]
MEAN_AIR_TEMP_1HR_25M	[Thermometer]
MEAN_VAPOR_PRESS_1HR_25M	[Laboratory Equipment]
MEAN_DOWN_SHRTWAVE_RAD_3HR_4M	[Laboratory Equipment]
MEAN_DOWN_SHRTWAVE_RAD_1HR_18M	[Laboratory Equipment]
MEAN_WIND_VELOCITY_1HR_18M	[Laboratory Equipment]
CRTFCN_CODE	[BORIS Designation]
REVISION_DATE	[BORIS Designation]

### 7.3.5 Data Range

The following table gives information about the parameter values found in the data files on the CD-ROM.

Column Name	Minimum Data Value	Maximum Data Value	Missng Data Value	Unrel Data Value	Below Detect Limit	Data Not Cllected
SITE_NAME	SSA-90A-FLXTR	SSA-OBS-FLXTR	None	None	None	None
SUB_SITE	9TE07-SAP01	9TE07-SAP02	None	None	None	None
DATE_OBS	23-MAY-94	23-OCT-96	None	None	None	None
TIME_OBS	0	2300	None	None	None	None
SPECIES	N/A	N/A	None	None	None	None
TREE_DESCR	N/A	N/A	None	None	None	Blank
MEASUREMENT_DESCR	N	xxxx	None	None	None	Blank
NUM_TREES	0	4	None	None	None	None
SAPFLOW_RATE	-15	152	-999	None	None	Blank
MEAN_SAPFLOW_RATE	-17.5	128	-999	None	None	Blank
MEAN_TRANS_RATE	-.067	.391	-999	None	None	Blank
MEAN_AIR_TEMP_1HR_	-14.6	33.3	-999	None	None	Blank

150CM							
MEAN_REL_HUM_1HR_	3.1	98.5	-999	None	None	Blank	
150CM							
MEAN_AIR_TEMP_3HR_	-6.5	34.8	-999	None	None	Blank	
240CM							
MEAN_REL_HUM_3HR_	11.5	99.1	-999	None	None	Blank	
240CM							
MEAN_AIR_TEMP_1HR_	-7	272	-999	None	None	Blank	
25M							
MEAN_VAPOR_PRESS_1HR_	166	2200	-999	None	None	Blank	
25M							
MEAN_DOWN_SHRTWAVE_	-1	662	-999	None	None	Blank	
RAD_3HR_4M							
MEAN_DOWN_SHRTWAVE_	-5	863	None	None	None	Blank	
RAD_1HR_18M							
MEAN_WIND_VELOCITY_	0	8	None	None	None	Blank	
1HR_18M							
CRTFCN_CODE	CPI	CPI	None	None	None	None	
REVISION_DATE	16-SEP-98	17-SEP-98	None	None	None	None	

-----

Minimum Data Value -- The minimum value found in the column.  
Maximum Data Value -- The maximum value found in the column.  
Missng Data Value -- The value that indicates missing data. This is used to indicate that an attempt was made to determine the parameter value, but the attempt was unsuccessful.  
Unrel Data Value -- The value that indicates unreliable data. This is used to indicate an attempt was made to determine the parameter value, but the value was deemed to be unreliable by the analysis personnel.  
Below Detect Limit -- The value that indicates parameter values below the instruments detection limits. This is used to indicate that an attempt was made to determine the parameter value, but the analysis personnel determined that the parameter value was below the detection limit of the instrumentation.  
Data Not Cllctd -- This value indicates that no attempt was made to determine the parameter value. This usually indicates that BORIS combined several similar but not identical data sets into the same data base table but this particular science team did not measure that parameter.

Blank -- Indicates that blank spaces are used to denote that type of value.  
N/A -- Indicates that the value is not applicable to the respective column.  
None -- Indicates that no values of that sort were found in the column.

-----

## 7.4 Sample Data Record

The following are wrapped versions of data record from a sample data file on the CD-ROM.

```
SITE_NAME, SUB_SITE, DATE_OBS, TIME_OBS, SPECIES, TREE_DESCR, MEASUREMENT_DESCR,  
NUM_TREES, SAPFLOW_RATE, MEAN_SAPFLOW_RATE, MEAN_TRANS_RATE,  
MEAN_AIR_TEMP_1HR_150CM, MEAN_REL_HUM_1HR_150CM, MEAN_AIR_TEMP_3HR_240CM,  
MEAN_REL_HUM_3HR_240CM, MEAN_AIR_TEMP_1HR_25M, MEAN_VAPOR_PRESS_1HR_25M,  
MEAN_DOWN_SHRTWAVE_RAD_3HR_4M, MEAN_DOWN_SHRTWAVE_RAD_1HR_18M,  
MEAN_WIND_VELOCITY_1HR_18M, CRTFCN_CODE, REVISION_DATE  
'SSA-90A-FLXTR', '9TE07-SAP02', 26-MAY-94, 2100, 'Populus tremuloides',  
'Early leafing clone', 'NNN', 3, 38.0, .102, , , -999.0, -999.0, , , , 'CPI', 16-SEP-98  
'SSA-90A-FLXTR', '9TE07-SAP02', 26-MAY-94, 2100, 'Populus tremuloides',  
'Late leafing clone', 'NNN', 3, 8.0, .102, , , -999.0, -999.0, , , , 'CPI', 16-SEP-98
```

## 8. Data Organization

### 8.1 Data Granularity

The smallest unit of data tracked by the BOREAS Information System (BORIS) was the data collected at a given site on a given date.

### 8.2 Data Format(s)

The Compact Disk-Read Only Memory (CD-ROM) files contain American Standard Code for Information Interchange (ASCII) numerical and character fields of varying length separated by commas. The character fields are enclosed with single apostrophe marks. There are no spaces between the fields.

Each data file on the CD-ROM has four header lines of HyperText Markup Language (HTML) code at the top. When viewed with a Web browser, this code displays header information (data set title, location, date, acknowledgments, etc.) and a series of HTML links to associated data files and related data sets. Line 5 of each data file is a list of the column names, and line 6 and following lines contain the actual data.

## 9. Data Manipulations

### 9.1 Formulae

#### 9.1.1 Derivation Techniques and Algorithms

Sap flux density (S) (cm/h) was calculated using the following equation derived from Marshall (1958):

$$S = 3600 k_{sw} \ln(T_u/T_l) / (x C_{p_w} \rho_w) \quad (1a)$$

where:  $x$  is the spacing between the heater and each thermocouple (0.75 cm)  
 $C_{p_w}$  is the specific heat (i.e. value for water is 4.18 J/(g °C))  
 $\rho_w$  is the density of sap (i.e., value for water is 1 g/cm<sup>3</sup>)

The thermal conductivity of active sapwood ( $k_{sw}$ ) was estimated at 0.0038 J/(cm s °C), based on the following (based on Swanson 1983):

$$k_{sw} = (k_w M \rho_b / \rho_w) + k_{dw} (1 - M \rho_b / \rho_w) \quad (1b)$$

where:  $k_w$  is the thermal conductivity of water (0.0060 J/(m s °C)).

$\rho_b$  is the typical live bulk density of sapwood (0.37 g/cm<sup>3</sup> for both aspen and spruce).

$M$  is the typical sapwood moisture content of 1.0 g moisture per g dry mass

The reported variation in aspen moisture content from 0.75 to 1.25 g/g, i.e., 100 ± 25%, would lead to ± 9% error in  $k_{sw}$  and resultant estimates of  $S$ . The longitudinal thermal conductivity of dry wood ( $k_{dw}$ ) was taken to be 0.00248 J/(cm s °C) based on  $\rho_b$  and the resultant void volume (Siau, 1971).

From equation (2a), conditions of zero sap flow can be identified when  $T_u = T_l$ . Ideally, this is applicable if probe spacing is exactly symmetrical and if wood heat transfer characteristics are precisely homogeneous above and below the heater. In practice, it was necessary to assume that zero sap flow occurred when the minimum value of mean  $S$  in each clone was reached (nights when VPD was near zero, excluding frost events). Thus, a zero offset ( $z$ ) was applied to obtain the "zeroed" sap flux density ( $S'$ ), where  $S' = z + S$ . The magnitude of  $z$  was constant, and normally within ± 0.5 cm/hr; it was recalculated, however, when probes were replaced.

The heat transfer theory indicates that the interruption of the sap stream by the probes results in an underestimation of the true sap flux density. For this implementation, wound width was estimated to be 2.0 to 2.2 mm, including a 0.2 to 0.3-mm zone of disturbed sapwood on each side of the holes following drilling (Swanson and Whitfield, 1981; Barrett et al., 1995). Simulations using a two-dimensional numerical model similar to Swanson and Whitfield (1981) indicated that with this implementation, a correction factor ( $a$ ) of approximately 2.0 is warranted to obtain the actual sap flux density ( $S^*$ ), where  $S^* = aS'$ . A similar underestimation of 45% (i.e.,  $a=1.8$ ) was observed by Cohen et al. (1981) for their implementation of the heat pulse method.

At each station, measurements of  $S^*$  were multiplied by the stand sapwood area to ground area ratio ( $SA$ ) to give estimates of canopy transpiration ( $E$ ).  $SA$  was determined as the product of  $BA$  and  $FSA$ , where  $BA$  is the basal area to ground area ratio of aspen stems (at 1.3-m height) in one 10-m x 10-m plot centered on each station, and  $FSA$  is the fraction of  $BA$  occupied by sapwood.  $FSA$  was calculated using two radial increment cores from each of four trees per station. The zone of active sapwood within increment cores was recognized from staining by a solution of methylene blue in methyl hydrate.

Measurements of  $BA$  and  $SA$  for each site monitored are described in Section 3 and given in Section 11.4.

## 9.2 Data Processing Sequence

Sap flow results were calculated using a custom-designed utility program (written in BASIC). The output file was then imported into a Quattro Pro spreadsheet, and bad data were flagged. Mean sap flux densities ( $S$ ) for up to three properly functioning trees per datalogger station were then calculated.

### 9.2.1 Processing Steps

- Uncorrected sap flux density ( $S$ ) from raw datalogger output was calculated based on equation 1a using a BASIC utility program.
- The output file was imported into a Quattro Pro spreadsheet.
- Data were graphed, and bad, anomalous, or missing data points were flagged.
- Average uncorrected sap flux density ( $S$ ) for each group of trees was calculated (normally two or three trees of a given species at each sap flow monitoring station). Data points flagged in step 3 were not included in the mean.
- For each portion of the data set where there were no changes in the number of properly functioning trees and no probe changes, the zero offset was determined as the difference between zero and the minimum  $S$  when the temperature was >0 °C.
- Zero offset was applied to the entire portion of the data set to give  $S'$  (see Section 9).
- Corrected sap flux density ( $S^*$ ) was obtained from  $S'$  by applying a multiplier ( $a=2.0$ ) to account for interruption of sap flow by probes (see Section 9).

- Transpiration at the stand level was estimated as follows:
  - Sapwood area to ground area ratio (SA) was determined for each species in each 10-m x 10-m plot.
  - SA of minor tree species (if present) was combined with SA of related major species (e.g., SA of balsam poplar, a minor species, was considered to be trembling aspen, the major species, for purposes of scaling).
  - For each species group, transpiration rate was estimated in each 10-m x 10-m plot as the product of  $S^*$  and SA.
  - For each species group, the transpiration rate for the site as a whole (e.g., SSA-OA) was determined as the average of the transpiration estimates from each 10-m x 10-m plot (i.e. datalogger station).
  - Total transpiration was estimated as the sum of the transpiration rates for all tree species.

### 9.2.2 Processing Changes

Since production of the previous data set in November 1994, the analysis method has been modified by incorporating the zero offset and the correction for sap flow interruption by probes. The method of flagging bad data has also been modified slightly.

## 9.3 Calculations

### 9.3.1 Special Corrections/Adjustments

For each period encompassing no probe changes and no loss of function by probes, a "zero offset" was determined by examining the deviation from zero of minimum flow on nonfreezing nights with negligible VPD. This resulted in a linear correction (usually  $<0.5$  cm/h) to all values of  $S$  to obtain  $S'$  (as described in Section 9).

### 9.3.2 Calculated Variables

$S$  Uncorrected sap flux density (cm/h)  $S'$  Zeroed sap flux density (cm/h)  $S^*$  Estimated actual sap flux density (cm/h) TRANS Estimated stand transpiration rate (mm/h)

## 9.4 Graphs and Plots

See BOREAS special issue publications (Hogg et al., 1997; Hogg and Hurdle, 1997).

# 10. Errors

## 10.1 Sources of Error

Potential errors in quantitative determinations of true sap flux density include:

- Freezing and thawing of xylem causes spiking of reported sap flow (including negative spikes). This can be readily recognized in the data sets by reference to air temperature data.
- Sapwood moisture content was generally not measured since it is a destructive procedure and most of the work was conducted in national parks. However, it can be reasonably assumed that it is near 1.0 (weight of moisture/weight of wood). Deviations from this assumption should normally lead to ( 10% error in  $S'$  (see Section 9). Diurnal variation in sapwood moisture content is assumed to be small and should not significantly affect the relative variation in  $S'$  (see Hogg et al., 1997).
- Sapwood bulk density can have a possible error of (10%, but this does not affect relative changes in  $S'$ .
- Problems in defining zero flow may lead to error of ca. 0.3 cm/h in  $S'$ .
- Variation in sap flux density with depth in xylem or by direction (all trees were probed on the north side to avoid thermal gradients caused by sun flecks) can lead to errors. This implementation partially integrates flow rates at different depths, but "spillage" of heat from sapwood into nonconducting heartwood may lead to underestimates of  $S'$  in trees with a very narrow sapwood zone (e.g., black spruce at SSA-OBS).

- The correction factor ( $a = 2.0$ , see Section 9) for sap flow interruption by sensors was dependent on a consistent width of xylem disruption following drilling and assumes that there was no progressive wounding response (see items h) and i) below). The appropriate correction factor was also dependent on the time interval between the heat pulse and when the temperature changes in sapwood were recorded (the correction would be reduced if the time interval were increased from 1 minute). However, a longer time interval would also reduce the signal-to-noise ratio. Also, because of this flow interruption, a reduction in sensitivity of up to 10% may occur at the maximum flow rates recorded (see Section 4.2.1.1). For these reasons, the correction factor may be in error by (10% (i.e.,  $a = 1.8$  to  $2.2$ )).
- Rapid, uneven heating or cooling of different regions of sapwood can lead to baseline drift. An attempt was made to minimize this by mounting probes on the north side of trees and by insulating the area in the vicinity of probes. This type of error can generally be recognized by the appearance of spiky (or incalculable) data, which were removed from the analysis. The cause is usually attributable to a visible symptom (removal of insulation by bears or bucks), direct sunlight on tree at a certain time of day, or a weak heat pulse, which amplifies the effect of any baseline drift).
- If moisture was trapped beneath the insulating layer around the probes, there was a tendency for reported sap flow values to decrease because of changes in heat transfer characteristics and/or wounding from fungal infections.
- Long-term implantation of probes in aspen (>2 to 3 months) usually resulted in a gradual, slight decline in sensitivity, typically in the range of 10 to 20% (possible wounding response). Thus, each probe was generally changed at least once during the growing season. For spruce, wounding responses and/or excessive resin from holes containing implanted probes may result in a more rapid reduction in sensitivity, although some trees maintain sensitivity over long time periods (3 to 4 months).
- Estimations of stand-level transpiration from sap flow data were also subject to statistical error (variation among trees and among patches of trees within the same stand).
- At SSA-OBS, the narrow (3 to 12 mm) width of sapwood probably led to significant underestimates of sap flux density, because of lateral heat transfer from the water-conducting sapwood into adjacent, nonconducting tissues. This would also lead to underestimates of stand transpiration rates based on sap flow measurements.

## 10.2 Quality Assessment

### 10.2.1 Data Validation by Source

The following two cross-comparisons are relevant here:

- A comparison of stand transpiration rates at SSA OA for the entire 1994 growing season, based on sap flow and tower-based eddy correlation measurements of latent flux above and below the aspen canopy (with Tower Flux (TF)-01, TF-02; Hogg et al., 1997; see also Black et al., 1996). With this comparison, total estimated transpiration of aspen (mid-June 1994 to mid-August 1994) using the scaled-up sap flow measurements was 15% lower than the most recent tower-based estimates (see Blanken et al., 1997).

A good correspondence was obtained when examining the overall seasonal pattern of transpiration by the two methods, and day-to-day variations in transpiration rates were similar (Hogg et al., 1997). On a mean diurnal basis, changes in sap flow lag behind changes in transpiration by about 1 hour, because of changes in water storage in the aspen stems and crowns.

- The constant power method of determining sap flow (TE-11, Bernard Saugier) was operated alongside the heat pulse method at the TE mixed wood site, from 28-Jul-1994 to 06-Aug-1994. The comparison was made for aspen, black spruce, and white spruce ( $n=2$  trees per species for the constant power method;  $n=4$  for aspen and  $n=2$  for black and white spruce for the heat pulse method).

The magnitude of daily mean sap flow ( $S^*$ ) by both methods was always within 15% for each of the 9 days, for both aspen and spruce (black and white spruce were combined in the analysis because of small sample sizes). The relative day-to-day pattern was also similar.

Differences in the diurnal pattern of sap flow were noted, however. The constant power method was relatively more "sluggish" for early to mid-morning values, and showed relatively greater maximum daytime values compared to the heat pulse method. This difference could be partly attributed to diurnal changes in heat storage with the constant power method.

### **10.2.2 Confidence Level/Accuracy Judgment**

In general, TE-07 is confident that this method can accurately determine relative changes in sap flow over periods of time ranging from 1 hour to a few weeks. Errors in the relative changes should be within (10%. This also applies to relative changes in the transpiration estimates, bearing in mind that there is typically a 0.5-to 1-hour diurnal lag between stem sap flow (at 1- to 1.5-m height) and transpiration.

Over longer time periods, wounding responses can introduce additional errors, which TE-07 attempted to minimize by periodic change in probes, regular maintenance, and removal of low-quality data. Nevertheless, relative changes on a full-season basis could be in error by as much as (25%.

Error in quantitative estimates of the actual sap flux density is difficult to assess, but based on the comparison with TE-11 (Section 10.2.1), error is probably (15% for aspen and spruce. However, progressive wounding responses can result in serious underestimations of sap flux density (such responses are usually evident from the data, and are normally corrected by changing probes).

From Section 10.1, it will be evident to the reader that there are many possible sources of error in estimating stand transpiration rates from sap flow measurements. In the 1994 comparison with eddy correlation measurements at SSA-OA, the estimates of transpiration were similar within 15%. This could indicate that much of the error listed in Section 10.1 is of minor consequence, but TE-07 nevertheless urges caution in applying these quantitative estimates of stand transpiration.

Tower-based eddy correlation is clearly a superior means of obtaining seasonal totals of water vapor flux at the stand level, since results can be rigorously validated by examining the degree of energy closure. However, sap flow measurements can have the following advantages over tower-based methods: 1) they are much less sensitive to meteorological conditions, resulting in more stable diurnal values; 2) all of the flux is attributable to water flux within a given tree; thus, they can provide a better means of examining transpiration responses for a given species. TE-07 experience indicates the benefits of operating sap flow measurements alongside eddy correlation, since the potential sources of error are different and generally independent.

### **10.2.3 Measurement Error for Parameters**

See Section 10.2.2.

### **10.2.4 Additional Quality Assessments**

None given.

### **10.2.5 Data Verification by Data Center**

Data were examined for general consistency and clarity.

## **11. Notes**

### **11.1 Limitations of the Data**

Potential sources of error are noted in Section 10. All of the sap flow data are for trees only; thus, transpiration estimates are not directly comparable to measurements of water vapor flux made above the canopy (which also include evaporation of intercepted water and transpiration by the understory and soil).

### **11.2 Known Problems with the Data**

In some instances, sample sizes (number of trees giving good measurements) was reduced because of animal damage, heater failure, thermal drift, and other causes. Discontinuities may occur in the data set when there is a loss of function for one or more trees at a given site, or following probe changes.

### 11.3 Usage Guidance

Readers are advised to examine all sections of this document to determine the suitability of this data set for their purposes. Any constructive feedback that users may have about the contents of this document and associated data sets is welcome. Scathing criticism will be cheerfully rebutted. "Let he/she who is without error in their own measurements throw the first stone."

Data may be viewed, transformed, or skewed in any fashion that suits the user's whim or needs. However, contact TE-07 (see Section 2.3) before using these data for presentations, publications, and related venues for the dissemination of erudite information.

### 11.4 Other Relevant Information

In the data files, the column called MEASUREMENT\_DESCR gives a coded description of the measurements taken. Each measurement taken is denoted by a single letter of code. The description code is:

- "a" to "h" means that trees called "a" to "h" gave good data.
- "N" denotes trees receiving new probes.
- "x" denotes missing or bad data taken from that tree.

The format design of the BOREAS data plan template seems to have been optimized for fluxers and remote sensors rather than for researchers in terrestrial ecology and physiology.

In lieu of humor and apologies, this section is hereby used to sneak in some ecological information relevant to these data sets.

### Section A: Description of Aspen Sites

The two aspen sites are both situated in stands of trembling aspen in central Saskatchewan, Canada. The boreal site is the BOREAS SSA-OA tower site, located in the southern boreal forest of Prince Albert National Park (PANP), elevation 600 m. The parkland site is located at Batoche National Historic Park, in the aspen parkland about 100 km to the south, elevation 500 m), midway between Saskatoon and Prince Albert. It is a CFS research site that forms part of the BFTCS (Price and Apps, 1995).

The two aspen sites differ dramatically, in terms of climate, vegetation, tree growth form, and productivity (see Hogg and Hurdle, 1995). Based on the 1951-80 climate normals (Environment Canada, 1982), the Batoche site receives considerably less precipitation (375 mm/yr at Rosthern, 52°40'N, 106°20'W) compared to the SSA OA site (462 mm/yr at Waskesui Lake, 53°55'N, 106°05'W). Furthermore, mean growing season temperatures at the Batoche site are about 2 °C warmer at the parkland site, resulting in a much drier long-term climate (see Hogg, 1994).

#### SSA-OA Site:

The vegetation of the SSA-OA site consists of an extensive, even-aged stand of trembling aspen, 70 to 80 years old and 18 to 22 m tall. The understory is dominated by beaked hazelnut (*Corylus cornuta* Marsh.) about 2 m tall. Aspen clones (patches of genetically identical trees) are readily distinguishable because of differences in bark characteristics and phenology. The stand is relatively homogeneous except for a few small openings and occasional patches of balsam poplar (*Populus balsamifera* L.). The site is gently rolling and generally well drained, with a predominantly clay loam soil texture.

In 1994, sap flow was monitored at a location about 1 km east of the main BOREAS flux tower. Two adjacent clones were monitored. They are referred to as the early-leafing (EL) and late-leafing (LL) clones, because of differences in phenology.

In 1996, sap flow was monitored at two locations near the main BOREAS flux tower. The first clone (PAA) was located near Hut B, where Remote Sensing Science (RSS)-17 monitored sap flow by the Granier method in 1994. The second clone (PAB) was situated near the canopy access tower located about 100 m east of the main flux tower.

### Batoche Site (CFS site and Auxiliary BOREAS site):

The parkland site is in one of the few remaining areas of native aspen parkland in the region that was never cultivated for agriculture. The terrain is rolling and underlain by stabilized sand dunes. The vegetation is highly heterogeneous, ranging from open native grassland with small, stunted clones of aspen to more productive lowland forests of aspen and balsam poplar with an understory of red osier dogwood (*Cornus stolonifera* Michx.). Trees are stunted in relation to diameter, and are often crooked, leaning, or forked, with heights ranging from <5 m to 15 m (see Hogg and Hurdle, 1995). Within the aspen stands, trees from two or more age classes are usually found (maximum age about 85 years). Dense bands of beaked hazelnut occur on north- and east- facing slopes, but in most areas, the forest understory consists of sparse grasses, herbs, and low shrubs (e.g., Saskatoon, *Amelanchier alnifolia* Nutt., choke-cherry, *Prunus virginiana* L., and prickly rose, *Rosa acicularis* Lindl.).

At the Batoche site, four stations were established along a 400-m transect extending from grassland to the forest interior, and three different trees were monitored each year at each station. One station was located in a small clone of stunted aspen surrounded by grassland (GL clone), two stations were located at the edge and in the center of a large (200 m x 75 m) clone in upland forest next to the grassland (UF clone), and one station was located in the center of a more mesic, lowland forest (LF clone).

### Stand Characteristics Of Aspen Sites Where Sap Flow Measurements Were Made:

#### General Stand Characteristics:

	SSA-OA	Batoche
Stand volume		
(cubic m per ha):	144*	32*
Leaf Area Index:	2.3**	1.4***
Height (m):	18-22	5-14
Age (years):	70-80	30-80

#### Notes:

- \* biometry surveys by Halliwell and Apps (1996)
- \*\* from Blanken et al. (1997)
- \*\*\* estimate based on litter traps

#### SSA-OA: Characteristics of clones monitored:

	1994		1996	
clone name:	EL	LL	PAA	PAB
diameter at 1.3 m ht (cm):	21-27	17-22	19-23	20-22
basal area ratio (sq. m per sq. m):	0.0039	0.0063	0.0046	0.0048
sapwood area ratio (sq. m per sq. m):	0.0020	0.0032	0.0032	0.0030

#### Batoche: Characteristics of clones monitored:

	Batoche 1994-1995			
clone name:	GL	UF	UF	LF
		edge	center	
height (m):	5	6- 8	12-14	7-10

diameter at 1.3 m ht (cm):	6-9	8-12	20-23	8-14
age (years):	30-45	30-45	70-80	30-55
basal area ratio (sq. m per sq. m):	0.0015	0.0015	0.0035	0.0017
sapwood area ratio (sq. m per sq. m):	0.0009	0.0010	0.0010	0.0011

Note: Data from UF (edge) were excluded in 1994 because of problems with wounding responses. Data from UF (center) were excluded from the 1995 analysis because of problems with thermal drift.

### Section B: Description Of Mixed Wood Site

This site is located near Candle Lake, Saskatchewan (53° 43.8'N, 105° 12.0'W), in the BOREAS SSA. It was used as an auxiliary site and had a canopy access tower for measurements by the TE-04 team (Joe Berry, principal investigator).

It is located on Saskatchewan forest inventory map E43 N595, on the NW side of Hwy 120 about 3 km east of southernmost turnoff into Candle Lake. The stand designation is 819/933, H15b ta a94/S5d BS a94. It is a small (180 m x 180 m) site of young (1940's origin) aspen-black spruce-white spruce mixed wood surrounded (to the north and west) by fen.

### Characteristics of Trees at Mixed Wood Site Where Sap Flow Measurements Were Made in 1994:

Species:	Black Spruce	White Spruce	Trembling Aspen	Balsam Poplar	Total
height (m):	7-8	7-8	11-13		
diameter at 1.3 m ht (cm):	11	11	12-16		
stem density* number per ha:	1400	300	1800	500	4000
Overall basal area ratio* (sq. m per sq. m):	0.00071	0.00020	0.00202	0.00045	0.00341
Overall sapwood area ratio* (sq. m per sq. m):	0.00040	0.00016	0.00158	(0.00035)	(0.0025)

Notes:

\*Based on average of four 10-m x 10-m plots

### Section C: Description of SSA-OBS Site

The SSA-OBS site (53°59'N, 105°07'W) is a BOREAS tower site located NE of Candle Lake, Saskatchewan, in the BOREAS SSA. It is dominated by an extensive stand of black spruce (*Picea mariana*) >100 years old. There is an understory of labrador tea (*Ledum groenlandicum*) and other sparse shrubs, and a surface moss layer dominated by *Pleurozium schreberi*, other feather mosses, and occasional hummocks of *Sphagnum* spp. The black spruce is highly variable in size, ranging up to ca. 15 m in height and about 15 cm in diameter. The forest is dominated by black spruce, with occasional large tamarack (*Larix laricina*) trees in the wettest areas and a few jack pine (*Pinus banksiana*) in the

drier areas. Stem density is generally high but variable.

### Characteristics of Trees at SSA-OBS Site Where Sap Flow Measurements Were Made in 1996:

Species:	Black Spruce	
Site:	BSA	BSB
height (m):	6-11	7-10
diameter at 1.3 m ht (cm):	5.5-12	7-11
stem density* number per ha:	9000	7000
Basal area ratio* (sq. m per sq. m):	0.0039	0.0028
Sapwood area ratio* (sq. m per sq. m):	0.00105	0.00082

Notes:

\*Based on 10-m x 10-m plot around each sap flow station

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## 12. Application of the Data Set

This data set can be used to study the sap flow rates, transpiration rates derived from the sap flow rates, and the environmental conditions affecting these rates of the boreal forest.

## 13. Future Modifications and Plans

No plans as of yet.

## 14. Software

### 14.1 Software Description

A utility program was used to process these data. It is written in QuickBasic and is presently not optimized for user friendliness.

### 14.2 Software Access

Contact TE-07 if interested in obtaining the QuickBasic program.

## **15. Data Access**

The sap flow data are available from the Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

### **15.1 Contact Information**

For BOREAS data and documentation please contact:

ORNL DAAC User Services  
Oak Ridge National Laboratory  
P.O. Box 2008 MS-6407  
Oak Ridge, TN 37831-6407  
Phone: (423) 241-3952  
Fax: (423) 574-4665  
E-mail: [ornl daac@ornl.gov](mailto:ornl daac@ornl.gov) or [ornl@eos.nasa.gov](mailto:ornl@eos.nasa.gov)

### **15.2 Data Center Identification**

Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics  
<http://www-eosdis.ornl.gov/>.

### **15.3 Procedures for Obtaining Data**

Users may obtain data directly through the ORNL DAAC online search and order system [<http://www-eosdis.ornl.gov/>] and the anonymous FTP site [<ftp://www-eosdis.ornl.gov/data/>] or by contacting User Services by electronic mail, telephone, fax, letter, or personal visit using the contact information in Section 15.1.

### **15.4 Data Center Status/Plans**

The ORNL DAAC is the primary source for BOREAS field measurement, image, GIS, and hardcopy data products. The BOREAS CD-ROM and data referenced or listed in inventories on the CD-ROM are available from the ORNL DAAC.

## **16. Output Products and Availability**

### **16.1 Tape Products**

None.

### **16.2 Film Products**

None.

### **16.3 Other Products**

These data are available on the BOREAS CD-ROM series.

## 17. References

### 17.1 Platform/Sensor/Instrument/Data Processing Documentation

P.A. Hurdle has a preliminary document outlining the technical configuration of the heat pulse method used here. Please contact TE-07 if interested in this document.

### 17.2 Journal Articles and Study Reports

Barrett, D.J., T.J. Hatton, J.E. Ash, and M.C. Ball. 1995. Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of south-eastern Australia. *Plant Cell Env.* 18:463-469.

Black, T.A., G. den Hartog, H.H. Neumann, P.D. Blanken, P.C. Yang, C. Russell, Z. Nestic, X. Lee, S.G. Chen, R. Staebler, and M.D. Novak. 1996. Annual cycles of water vapor and carbon dioxide fluxes in and above a boreal aspen forest. *Global Change Biol.* 2: 219-229.

Blanken, P.D., T.A. Black, P.C. Yang, H.H. Neumann, Z. Nestic, R. Staebler, G. den Hartog, M.D. Novak, and X. Lee. 1997. Energy balance and canopy conductance of a boreal aspen forest: Partitioning overstory and understory components. *Journal of Geophysical Research* 102(D24):28,915-28,927.

Cohen, Y., M. Fuchs, and G.C. Green. 1981. Improvements of the heat pulse method for determining sap flow in trees. *Plant Cell Env.* 4:391-397.

Environment Canada. 1982. Canadian climatic normals 1951-1980. Temperature and precipitation. Prairie Provinces. Atmospheric Environment Service, Downsview, Ontario, Canada, 429 pp.

Halliwell, D. and M.J. Apps. 1996. BOREAS biometry and auxiliary sites. Overstory and understory data, Version 2. Canadian Forest Service, Edmonton, Alberta, 256 p.

Hogg, E.H. 1994. Climate and the southern limit of the western Canadian boreal forest. *Can. J. For. Res.* 24:1835-1845.

Hogg, E.H. 1997. Temporal scaling of moisture and the forest-grassland boundary in western Canada. *Agric. Forest Meteorol.* 84: 115-122.

Hogg, E.H. and P.A. Hurdle. 1995. The aspen parkland in western Canada: a dry-climate analogue for the future boreal forest? *Water Air Soil Pollut.* 82:391-400.

Hogg, E.H. and P.A. Hurdle. 1995. Responses of sap flow in aspen(*Populus tremuloides*) to vapor pressure deficit in the boreal forest and aspen parkland of central Saskatchewan, Canada. Abstracts of presentations at the 80th Annual Ecological Society of America Meeting, 30-July-1995 to 03-August-1995, Snowbird, Utah.

Hogg, E.H. and P.A. Hurdle. 1997. Sap flow in trembling aspen: implications of stomatal responses to vapor pressure deficit. *Tree Physiology*, 17:501-509 (BOREAS Special Issue).

Hogg, E.H., T.A. Black, G. den Hartog, H.H. Neumann, R. Zimmermann, P.A. Hurdle, P.D. Blanken, Z. Nestic, P.C. Yang, R.M. Staebler, K.C. McDonald, and R. Oren. 1997. A comparison of sap flow and eddy fluxes of water vapor from a boreal deciduous forest. *Journal of Geophysical Research* 102(D24):28,929-28,937.

Marshall, D.C. 1958. Measurement of sap flow in conifers by heat transport. *Plant Physiol.* 33:385-396.

Newcomer, J., D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers, eds. 2000. Collected Data of The Boreal Ecosystem-Atmosphere Study. NASA. CD-ROM.

Price, D.T. and M.J. Apps. 1995. The Boreal Forest Transect Case Study: global change effects on ecosystem processes and carbon dynamics in boreal Canada. *Water Air Soil Pollut.* 82:203-214.

Sellers, P. and F. Hall. 1994. Boreal Ecosystem-Atmosphere Study: Experiment Plan. Version 1994-3.0, NASA BOREAS Report (EXPLAN 94).

Sellers, P. and F. Hall. 1996. Boreal Ecosystem-Atmosphere Study: Experiment Plan. Version 1996-2.0, NASA BOREAS Report (EXPLAN 96).

Sellers, P., F. Hall, and K.F. Huemmrich. 1996. Boreal Ecosystem-Atmosphere Study: 1994 Operations. NASA BOREAS Report (OPS DOC 94).

Sellers, P., F. Hall, and K.F. Huemmrich. 1997. Boreal Ecosystem-Atmosphere Study: 1996 Operations. NASA BOREAS Report (OPS DOC 96).

Sellers, P., F. Hall, H. Margolis, B. Kelly, D. Baldocchi, G. den Hartog, J. Cihlar, M.G. Ryan, B. Goodison, P. Crill, K.J. Ranson, D. Lettenmaier, and D.E. Wickland. 1995. The boreal ecosystem-atmosphere study (BOREAS): an overview and early results from the 1994 field year. *Bulletin of the American Meteorological Society.* 76(9):1549-1577.

Sellers, P.J., F.G. Hall, R.D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K.J. Ranson, P.M. Crill, D.P. Lettenmaier, H. Margolis, J. Cihlar, J. Newcomer, D. Fitzjarrald, P.G. Jarvis, S.T. Gower, D. Halliwell, D. Williams, B. Goodison, D.E. Wickland, and F.E. Guertin. 1997. BOREAS in 1997: Experiment Overview, Scientific Results and Future Directions. *Journal of Geophysical Research* 102(D24): 28,731-28,770.

Siau, J.F. 1971. Flow in wood. Syracuse Wood Science Series 1. Syracuse University Press. 131 p.

Swanson, R.H. 1983. Numerical and experimental analyses of implanted-probe heat pulse velocity theory. Ph.D. thesis, University of Alberta, 298 p.

Swanson, R.H. 1994. Significant historical developments in thermal methods for measuring sap flow in trees. *Agric. For. Meteorol.* 72:113-132.

Swanson, R.H. and D.W.A. Whitfield. 1981. A numerical analysis of heat pulse velocity theory and practice. *J. Exp. Bot.* 32:221-239.

### **17.3 Archive/DBMS Usage Documentation**

None.

## **18. Glossary of Terms**

aerodynamic conductance - In this context, a measure of the degree to which vertical air movement permits the transfer of water vapor and sensible heat between the leaf surface and a reference height above the forest canopy.

BA (basal "area") - In this context, the ratio of tree basal area (at 1.3 m height) to ground area, as measured within plots in the forest stand being monitored.

boreal forest - Northern forest that occurs at high latitudes in Canada, Alaska, Russia, and Scandinavia. In western Canada, it can be defined as a forested, cold-climate region where there are peatlands (bogs and/or fens) and at least three species of conifers (typically white spruce, black spruce, and tamarack; and usually either jack pine or lodgepole pine). Trembling aspen is often abundant or dominant, but the diversity of other hardwood tree species is low.

canopy conductance - In this context, a measure of the degree to which stomata and plant surfaces in the canopy permit passage of water vapor, expressed on a ground area basis.

clone - A group of genetically identical trees that occurs in species that reproduce vegetatively, including trembling aspen and balsam poplar. Typically a clone of aspen consists of dozens to hundreds of trees, occupying areas of up to several hectares in the boreal region.

eddy correlation - A micrometeorological technique used extensively in BOREAS to measure the exchange of water vapor, heat, carbon dioxide, and trace gases between the forest and the atmosphere. Eddy correlation measurements in BOREAS were made from towers (above or below the forest canopy) and from aircraft. In simple terms, the technique involves simultaneous, high-frequency measurements of vertical air movement and the quantities of interest.

FSA - Fraction of total tree basal area that is sapwood, as estimated using increment cores.

latent heat flux density - The rate of energy exchange (e.g., from the landscape) caused by evaporation of water (including transpiration), expressed in watts per square meter ground area. This can also be expressed in mm per hour of water vapor loss from the landscape.

leaf water potential - A measure of plant water status, inferred as the negative value of the pressure required to restore moisture to the cut surface of xylem in a leaf petiole or twig when the latter is enclosed by a pressure chamber.

parkland - A semi-arid vegetation zone in western Canada that is transitional between the boreal forest and prairies to the south. Conifers such as spruce and pine are generally absent, and forest cover is generally restricted to stunted patches of aspen. Peatlands (bogs and fens) are generally absent, and small lakes tend to dry up during periods of drought. This zone is intensively cultivated for agriculture.

sap flow - General term referring to the upward movement of liquid water within trees and other plants.

sap flux density - Quantitative measure of the volume of liquid water moving upward per unit area of sapwood in trees.

sapwood - Water-conducting tissue in trees, consisting of the outermost and youngest region of xylem. For the major boreal tree species, this typically consists of the "wood" formed in the past 10-25 years.

SA (sapwood "area") - In this context, the ratio of sapwood area (at 1.3-m height) to ground area, as measured within plots in the forest stand being monitored.

sensible heat flux density - The total rate of energy exchange (e.g., from the landscape) by convection or conduction of heat, expressed in watts per square meter ground area.

stomata - Little holes in leaves that provide a pathway for water vapor loss from leaves and for the exchange of carbon dioxide with the atmosphere.

stomatal conductance - A measure of the degree to which stomata permit the passage of water vapor or carbon dioxide, expressed on a leaf area basis.

transpiration - In this context, refers to water vapor loss through the stomata of tree leaves.

vapor pressure deficit (VPD) - Difference between the actual vapor pressure and the saturation vapor pressure of air, as measured at a reference height within or above the forest canopy.

xylem - Water-conducting tissue in plants; in trees we are referring to secondary xylem or what the lay person would view as "wood," which also serves as structural support for the tree.

## 19. List of Acronyms

ASCII	- American Standard Code for Information Interchange
Batoche	- The study site located in the Batoche National Historic Park
BFTCS	- Boreal Forest Transect Case Study
BOREAS	- BOREal Ecosystem-Atmosphere Study
BORIS	- BOREAS Information System
CD-ROM	- Compact Disk-Read Only memory
CFS	- Canadian Forest Service
DAAC	- Distributed Active Archive Center
DOY	- Julian Day of Year
EOS	- Earth Observing System
EOSDIS	- EOS Data and Information System
GIS	- Geographic Information System
GMT	- Greenwich Mean Time
GSFC	- Goddard Space Flight Center
HTML	- HyperText Markup Language
IFC	- Intensive Field Campaign
MIX	- Mixed Wood
NAD83	- North American Datum of 1983
NASA	- National Aeronautics and Space Administration
NOAA	- National Oceanic and Atmospheric Administration
NSA	- Northern Study Area
ORNL	- Oak Ridge National Laboratory
PANP	- Prince Albert National Park
RSS	- Remote Sensing Science
S	- Sap Flux Density
SSA	- Southern Study Area
SSA-OA	- Old Aspen
SSA-OBS	- Old Black Spruce
T_l	- Temperature at the lower thermocouple
T_u	- Temperature at the upper thermocouple
TE	- Terrestrial Ecology
TF	- Tower Flux
URL	- Uniform Resource Locator
UTM	- Universal Transverse Mercator
VPD	- Vapor Pressure Deficit

## **20. Document Information**

### **20.1 Document Revision Date**

Written: 03-Oct-1996

Last Updated: 11-Aug-1999

### **20.2 Document Review Date(s)**

BORIS Review: 10-Oct-1997

Science Review:

### **20.3 Document ID**

### **20.4 Citation**

When using these data, please include the following acknowledgment as well as citations of relevant papers in Section 17.2:

E.H. (Ted) Hogg and P.A. Hurdle, CFS

If using data from the BOREAS CD-ROM series, also reference the data as:

Hogg, E.H., "Climate Change Effects on Net Primary Productivity of Productivity of Aspen and Jack Pine at the Southern Limit of the Boreal Forest." In *Collected Data of The Boreal Ecosystem-Atmosphere Study*. Eds. J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. CD-ROM. NASA, 2000.

Also, cite the BOREAS CD-ROM set as:

Newcomer, J., D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers, eds. *Collected Data of The Boreal Ecosystem-Atmosphere Study*. NASA. CD-ROM. NASA, 2000.

### **20.5 Document Curator**

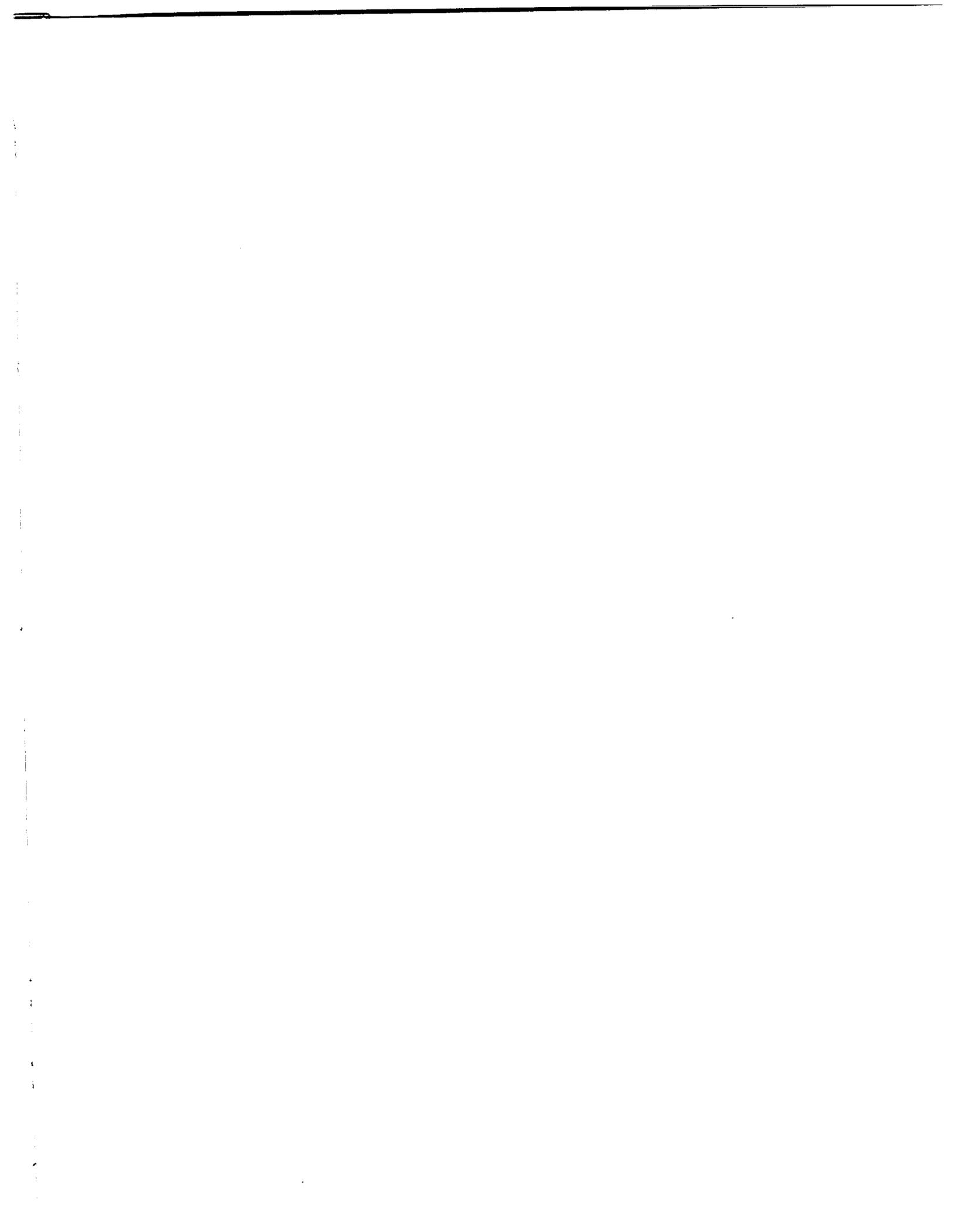
### **20.6 Document URL**

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

<b>1. AGENCY USE ONLY (Leave blank)</b>		<b>2. REPORT DATE</b> October 2000	<b>3. REPORT TYPE AND DATES COVERED</b> Technical Memorandum	
<b>4. TITLE AND SUBTITLE</b> Technical Report Series on the Boreal Ecosystem-Atmosphere Study (BOREAS) BOREAS TE-7 Sap Flow Data			<b>5. FUNDING NUMBERS</b>  923 RTOP: 923-462-33-01	
<b>6. AUTHOR(S)</b> E.H. Hogg and P.A. Hurdle Forrest G. Hall and Andrea Papagno, Editors				
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS (ES)</b>  Goddard Space Flight Center Greenbelt, Maryland 20771			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  2000-03136-0	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS (ES)</b>  National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING / MONITORING AGENCY REPORT NUMBER</b>  TM—2000—209891 Vol. 150	
<b>11. SUPPLEMENTARY NOTES</b> E.H. Hogg and P.A. Hurdle: Canadian Forest Service, Edmonton, Alberta, Canada; A. Papagno: Raytheon ITSS, NASA Goddard Space Flight Center, Greenbelt, Maryland				
<b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b> Unclassified—Unlimited Subject Category: 43 Report available from the NASA Center for AeroSpace Information, 7121 Standard Drive, Hanover, MD 21076-1320. (301) 621-0390.			<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT (Maximum 200 words)</b>  The BOREAS TE-7 team collected data sets in support of its efforts to characterize and interpret information on the sap flow of boreal vegetation. The heat pulse method was used to monitor sap flow and to estimate rates of transpiration from aspen, black spruce, and mixed wood forests at the SSA-OA, MIX, SSA-OBS, and Batoche sites in Saskatchewan, Canada. Measurements were made at the various sites from May to October 1994, May to October 1995, and April to October 1996. A scaling procedure was used to estimate canopy transpiration rates from the sap flow measurements. The data were stored in tabular ASCII files. Analyses to date show a tendency for sap flow in aspen to remain remarkably constant over a wide range of environmental conditions VPD from 1.0 to 4.8 kPa and solar radiation >400 W/m <sup>2</sup> ). For forests with high aerodynamic conductance, the results would indicate an inverse relationship between stomatal conductance and VPD, for VPD >1 kPa. A possible interpretation is that stomata are operating to maintain leaf water potentials above a critical minimum value, which in turn places a maximum value on the rate of sap flow that can be sustained by the tree.				
<b>14. SUBJECT TERMS</b> BOREAS, terrestrial ecology, sap flow.			<b>15. NUMBER OF PAGES</b> 27	
			<b>16. PRICE CODE</b>	
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b> UL	



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